Optimizing Water Delivery System Storage and Its Influence on Air Pollutant Emission Reduction

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Abstract—This paper presents a quantitative approach to estimating the carbon dioxide (CO_2) emission reduction by optimizing water storage operations in water delivery systems. This approach uses hydraulic models of water delivery systems to perform pumping energy optimization analyses with equalization water storage and identifies real-time electrical generation types based on Locational Marginal Price (LMP) data available in open electrical markets. The real-time pollutant emission reduction has been evaluated based on hourly on-duty generation types and pollutant emission rates for different types of generation. An example is presented that applied the proposed approach to a large water delivery system in the Metro Detroit area, Michigan. The analysis results showed a daily CO_2 emission reduction of 26.1 tonnes, which accounted for approximately 3% of the total CO_2 emission produced by the electricity consumption for pumping water under the maximum day demand condition of 2012.

Keywords—water delivery; storage; optimization; air pollutant; emission reduction; generation; locational marginal price (LMP).

I. INTRODUCTION

The accumulation of carbon dioxide (CO_2) in the atmosphere is recognized as a major contributor to the global warming problem. Reducing carbon and other air pollutants emissions is an immense issue for protecting our environment. In 2011, the total U.S. emission of CO_2 was 5,420 million tonnes, the second largest CO_2 emitter country in the world. The U.S. emission of CO_2 by the electricity generation section in 2011 was 2,166 million tonnes, or about 40% of total U.S. CO_2 emissions [1]. Potable water delivery in the U.S. accounts for 3% of the nation's electricity consumption, which generates an annual CO_2 emission of approximately 64 million tonnes [2].

Various energy resources have been used for electricity generation including nuclear, coal, natural gas, fuel oil and renewable fuels like hydroelectric, geothermal, solar, and biomass. Nuclear and renewable generators do not discharge air pollutants. The other fossil fuel based types of power plants emit air pollutants and are normally less environmental-friendly.

Power plants are classified as base plants and peaking plants based on their operational status to meet the diurnal variation of energy demand in a region. Base plants produce electricity at a constant rate and are operated year-round to meet some or all of a given region's continuous demand. They usually use coal, nuclear or renewable fuels. Peaking plants operate primarily when power use is at its peak and are often powered by natural gas or fuel oil.

Water utilities pay an electrical demand charge in addition to a usage fee. The electrical usage is the energy that a water utility consumes and is measured in kilowatt-hours (kWh). The electric demand represents the highest rate of electrical current during a billing period and is measured in kilowatts (kW).

The electrical demand charge will be a large part of the energy bill if a water utility operates its pumping facilities to directly serve water demands without storage. During peak water demand hours many utilities use stored water to serve part of the on-peak demands to reduce the on-peak pumping requirements. This allows the pumping facilities to operate at a constant or less variable pumping rate to reduce peak electric demand.

Numerous water storage optimization studies have been performed with a focus on minimizing pumping energy use and costs [3, 4]. However, little consideration has been given to the environmental effects of optimizing water storage operations even though it is generally assumed that a reduction of energy consumption results in reduction of air pollutant emissions. To assess the environmental effects of optimizing storage operations in water delivery systems, appropriate methodologies are required to evaluate the pollutant emission reduction.

Many water distribution systems do not own enough storage capacity to supplement their peak-demand water delivery. Instead, they adjust pumping to roughly match the water system demand variations. Under this operation mode, more water is pumped during peak hour periods and less water is pumped during off-peak hours. Consequently, adding more water storage would help these utilities reduce energy costs. Water is pumped to storage during off-peak hours and storage is used to serve the demands during peak hours so that water utilities are able to run their pumps at constant or near constant rates for both on-peak and off-peak periods.

Peaking plants powered by natural gas and fuel oil produce higher pollutant emissions. Therefore, shifting on-peak electrical demands to off-peak hours by using water storage would reduce air pollutant emissions. This paper presents a quantitative approach that estimates the potential CO_2 emission with water delivery system model simulation and the available Locational Marginal Price (LMP) data in electricity markets.

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II. APPROACH

To evaluate storage capacity and pumping optimization in a water delivery system and its influence on air pollutant emissions, a calibrated hydraulic computer model is required. If the existing storage facilities are unable to meet water delivery requirements, necessary cyber storages are added to the hydraulic model to meet the requirements.

The operation of actual and cyber water storages in the water delivery system is subjected to an optimization analysis with the computer model. The location, type and size of the cyber storages can be adjusted to optimize the hourly energy requirements. This is done by: (1) shifting part of the peak hour pumping requirements to the off-peak period to reduce the electrical demand for the water delivery and (2) minimizing the total energy use for pumping water.

To optimize pollutant emissions based on energy consumption, diurnal variation data of the on-duty generator types is required because the emission rates are different for each type of generation.

Using the LMP data available in electricity markets to distinguish diurnal variations of marginal generation type is proposed [5]. According to the generation data collected for the power grids of the Midwest Independent Transmission System Operator (MISO), the relationship between LMPs and marginal generation types was developed and is summarized in Table I.

TABLE I. LMP RANGES FOR MARGINAL GENERATION

Marginal Generator Type	Upper Bound LMP ($)
Nuclear/Renewable	19.25
Coal	78.88
Combined Cycle Natural Gas	128.58
Other Natural Gas	140.28
Residual Fuel Oil	202.2
Simple Cycle Natural Gas	277.11
Distillate Fuel Oil	>277.11

Finally, the pollution emission rates for different types of electric generation are required to quantify the amount of emissions that can be reduced by utilizing water storage and shifting on-peak pumping requirements in a water delivery system. The emission rates for certain key pollutants, including CO_2, are available in EPA's eGRID (Emissions & Generation Resource Integrated Database) [6]. The CO_2 emission rates for different types of generation are presented in Table II.

TABLE II. CO_2 EMISSION RATES FOR DIFFERENT GENERATION

Marginal Generator Type	CO_2 (lbs/kWh)
Nuclear/Renewable	0.00
Coal	2.07
Natural Gas	2.29
Distillate Fuel Oil	2.54

III. EXAMPLE OF APPLICATION

To assess environmental effects by optimizing storage use for water delivery, the water delivery system in the Metro Detroit area has been studied. The Metro Detroit area is the metropolitan area located in Southeast Michigan, having a population of approximately 4 million that makes up about 40% of Michigan's population. The water demand for the majority of the people in the Metro Detroit area is served by the Detroit Water and Sewerage Department (DWSD) water transmission system.

A. Water System Overview

DWSD's water system is one of the largest systems in the nation, which serves the City of Detroit and 127 whole-sale customer communities located in eight counties throughout the Metro Detroit area. DWSD delivers water to the communities' water distribution systems or its retail customers via its 21 pumping stations and 3,840 miles of transmission and distribution mains. DWSD's water network is supplied by five water treatment plants [7, 8]. In 2012, the five water treatment plants delivered a total of 203 billion gallons of water to the customers. That represents a daily average water delivery of 556 MGD. A schematic of DWSD water system is shown in Figure 1.

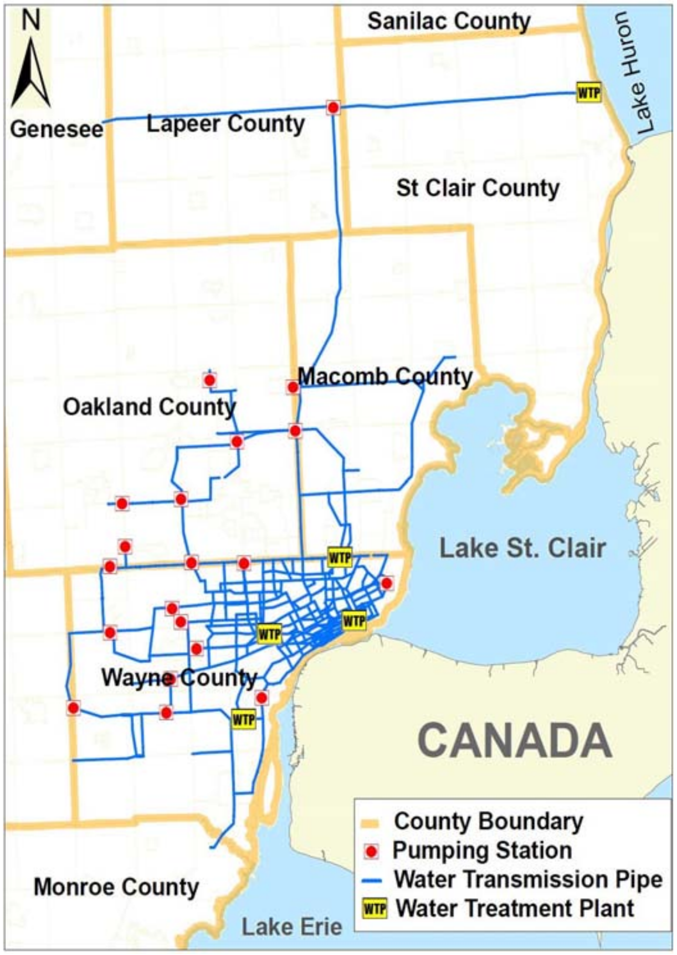

Figure 1. Schematic of DWSD Water System

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Currently, DWSD does not operate any elevated storage tanks. Instead, it uses 20 at-grade storage reservoirs with a total capacity of 173 MG. The storage reservoirs are located at most of its pumping stations to provide additional water during peak demands when the five water treatment plants are supplying at maximum capacity.

B. *Optimizing Water Storage in the System*

According to the supervisory control and data acquisition (SCADA) records, DWSD system's maximum day demand in 2012 was 960 MGD on June 27, 2012. DWSD's water transmission system model, which represented the 2012 maximum day demand condition, was developed and used to investigate needs for additional water storage for the water system. Simulations for optimizing operations of water storages were conducted to identify the locations where additional water storage would help reduce on-peak pumping requirements. The simulation results identified 12 water distribution systems that are currently operated by the corresponding DWSD's whole-sale customers and use little or no water storage. The population served by these water distribution systems is approximately 1 million with a maximum day demand of 256 MGD in 2012. The identified distribution systems, approximate population and maximum demands are summarized in Table III.

TABLE III. POPULATION & WATER DEMAND IN SYSTEMS

Distribution System Name	2012 Population	Maximum Day Demand (MGD)
City of Sterling Heights System	129,900	34.1
City of Warren System	134,200	30.3
City of Livonia System	96,000	29.8
City of Troy System	81,500	26.7
City of Farmington Hills System	80,300	21.5
Shelby Township System	73,800	20.2
Macomb Township System	79,600	19.5
Clinton Township System	96,800	18.8
City of Rochester Hills System	71,500	18.0
Canton Township System	76,400	13.4
City of Westland System	83,200	12.5
City of Novi System	55,600	11.3
Total	***1,058,800***	***256.0***

Due to no water storage in the distribution systems, DWSD supplies these communities by pumping to meet demands. During peak hours, DWSD uses reservoir pumps to pump water from its at-grade water reservoirs to provide additional water beyond the amount that is pumped through the booster pumps. Model simulations found that the use of reservoirs and reservoir pumps consumed significantly more energy. This was because: (1) the majority of the pressure energy associated with reservoir-filling water (35 to 50 PSI on average in DWSD's system) was lost when the water was filling the reservoirs; (2) reservoir pumps require more energy to raise additional water head to match the hydraulic grade provided by the booster pumps located in the same pumping station that serves the peak hour water demands; and (3) energy use for both reservoir pumping and line pumping applies a high peak hour load on the power transmission grids that serve DWSD. Since more than one of the 12 identified distribution systems are supplied by the same one or couple of DWSD's pumping stations, the systems were divided into five community groups based on locations and relationships to the DWSD's pumping stations. The identified groups are shown in Table IV.

The peak hour pumping energy requirements were evaluated for the two following scenarios: (1) directly pumping to meet demands with no water storage in the studied distribution systems; and (2) optimizing pumping operations with added cyber water storages in each of the studied systems.

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TABLE IV. IDENTIFIED COMMUNITY GROUPS

Distribution System Name	Group No.	Maximum Day Demand (MGD)
City of Livonia System	1	55.63
Canton Township System		
City of Westland System		
City of Farmington Hills System	2	59.48
City of Troy System		
City of Novi System		
City of Rochester Hills System	3	38.24
Shelby Township System		
City of Warren System	4	64.41
City of Sterling Heights System		
Clinton Township System	5	38.27
Macomb Township System		

The water storage facilities used in simulating the second scenario include elevated tanks and at-grade reservoirs. Since the detailed information is not available for some of the studied distribution systems to determine the required size for elevated tanks or at-grade reservoirs, it was assumed in the simulations that one third of the required storage capacity was equipped with elevated tanks and the remaining storage capacity was realized as at-grade reservoirs. The effective water storage volumes for each of the five community groups were identified by model simulations. A summary of the simulation results is presented in Table V. The on-peak pumpage reduction for each of the five community groups is presented in Figures 2 through 6.

TABLE V. REQUIRED WATER STORAGE & ENERGY USE REDUCTION

Community Group	Required Effective Water Storage (MG)	On-peak Energy Use Reduction (kWh)
1	5.07	5,141
2	5.57	5,648
3	5.24	5,309
4	6.87	6,959
5	4.64	4,700
Total	27.39	27,757

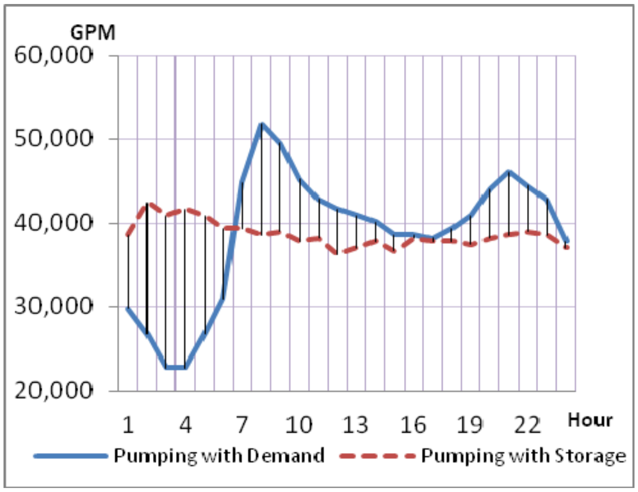

Figure 2. Pumpage Comparison for Group 1

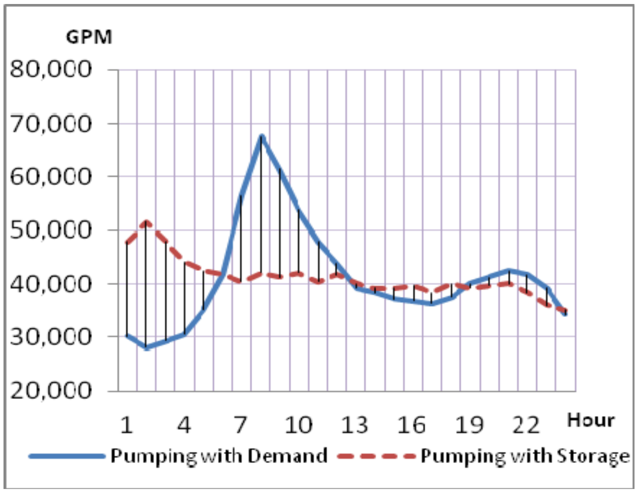

Figure 3. Pumpage Comparison for Group 2

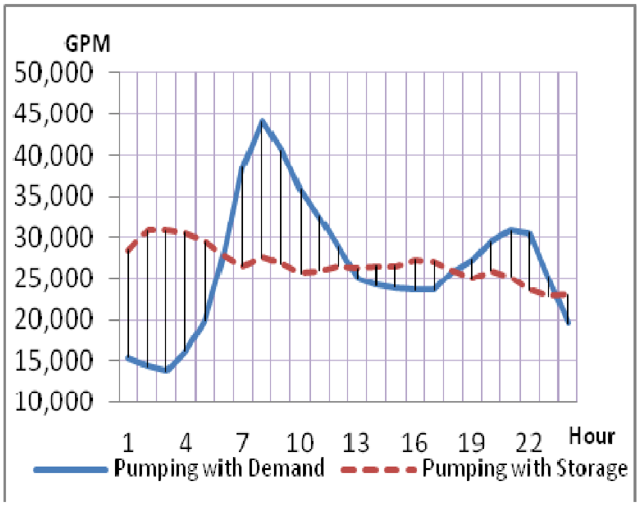

Figure 4. Pumpage Comparison for Group 3

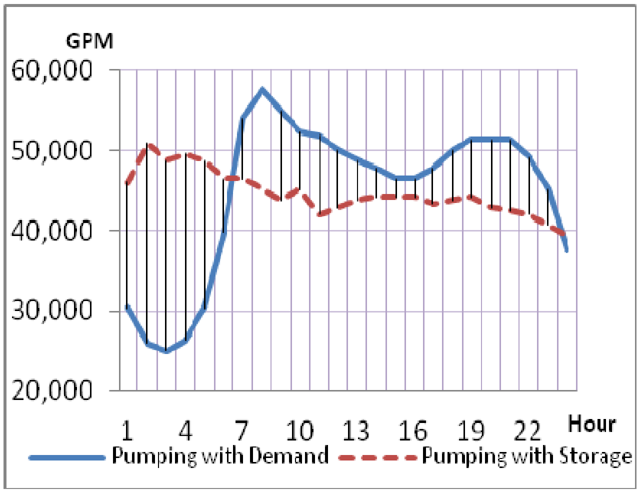

Figure 5. Pumpage Comparison for Group 4

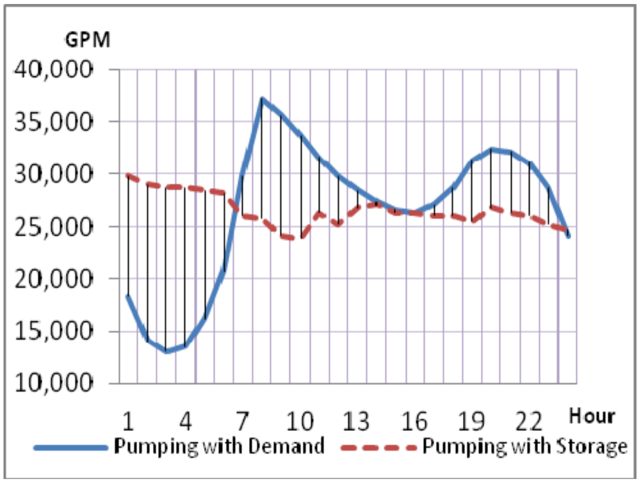

Figure 6. Pumpage Comparison for Group 5

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C. *Determining Hourly Marginal Generation Types*

Since the time-sensitive marginal generation types can be determined based on the corresponding hourly LMPs [5], the LMP's for the date of June 27th, 2012 were downloaded from MISO's website. The power plant closest to the studied area is DTE Energy's St. Clair Power Plant. The LMP data for the LMP nodes, which represent the generations at the St. Clair Power Plant, was used to determine the hourly generation types. The hourly LMP data and the corresponding generation types are presented in Table VI. The generation types were determined according to the criteria in Table I.

TABLE VI. LMPS FOR ST. CLAIR PLANT ON JUNE 27, 2012

Time	**MISO's Avg. LMP ($)**	**Type of Marginal Generation**
1:00	9.66	Nuclear/Renewable
2:00	13.19	Nuclear/Renewable
3:00	-2.38	Nuclear/Renewable
4:00	14.78	Nuclear/Renewable
5:00	16.51	Nuclear/Renewable
6:00	19.44	Coal
7:00	22.16	Coal
8:00	20.96	Coal
9:00	23.57	Coal
10:00	22.63	Coal
11:00	23.42	Coal
12:00	24.68	Coal
13:00	24.70	Coal
14:00	27.53	Coal
15:00	27.97	Coal
16:00	108.82	Coal
17:00	49.86	Coal
18:00	44.29	Coal
19:00	56.71	Coal
20:00	48.37	Coal
21:00	33.58	Coal
22:00	33.12	Coal
23:00	24.43	Coal
24:00	23.40	Coal

D. *Estimating CO_2 Emission Reduction*

Based on the simulation results, using water storage at a capacity of 27.4 MG to minimize DWSD's pumpage during the on-peak demand periods (from approximately 6 a.m. to 10 a.m. and from approximately 6 p.m. to 10 p.m.) results in a reduction of energy use of 27,757 kWh. Since the marginal generation type for these hours was coal, according to U.S. EPA eGRID, the CO_2 emission rate for coal generation was calculated as 2.07 lbs/kWh. The marginal generation from midnight to 5 a.m. was nuclear or renewable fuel that produced no CO_2 emission, so the total CO_2 emission reduction was calculated only for the remaining 19 hours when the marginal generation was coal. The identified CO_2 emission reduction by utilizing water storages on the maximum demand day is 57,457 lbs (26.1 tonnes), which accounts for approximately 3% less emission than that produced by the operating the system without water storage in the selected distribution systems. A summary of the on-peak pumping and CO_2 emission under the two operational conditions is presented in Table VII.

TABLE VII. CO_2 EMISSION REDUCTION BY PUMPING WITH STORAGE

Pumping Scenario	**On-Peak Pumpage (MG)**	**Energy Used for Pumping (kWh)**	**Emission of CO_2 (tonnes)**
Pumping without Storage	202	920,347	864.0
Pumping with Storage	175	892,590	837.9
Reduction	27	27,757	26.1

IV. CONCLUSION

Since considerable energy consumption is associated with pumping in water delivery systems, optimizing water storage would lead to reduction in energy requirements and likely some pollutant emissions. Based on the optimization analysis described in this paper, the daily emission reduction by optimizing water storage operations can be evaluated.

An example of using the proposed quantitative approach to evaluate potential emission reduction is presented. The water storage optimization analysis, which was based on the MISO's LMP data and the DWSD water transmission system model, identified a CO_2 emission reduction of 3%. The study results showed the approach is useful to evaluate the carbon emission reduction based on optimizing water storage to minimize on-peak energy requirements in a water delivery system. The environmental effect would be greater if additional storage capacity was added to a water delivery system that currently does not have enough equalization storage volume.

Further studies are needed to optimize water storage and pumping operations based not only on reduction in energy consumption but also in pollutant emissions. Aside from CO_2 emission reduction, effects of optimizing water delivery storage on the emission reduction for other key air pollutants will be studied as well.

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